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TREE GROWTH AND CLIMATIC CYCLES¹

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THIS paper discusses certain variations in the width of the annual rings of trees that suggest, through climate, a relationship to the sunspot cycle. Since tree rings form the vehicle in which the variations are found, some reference to them is necessary by way of introduction.

The total number of rings carefully examined as to growth date is well over half a million. They are grouped in some 5,000 specimens, mostly different trees. About 250,000 rings have been measured with care after accurate dating in all cases, except, of course, the geological rings. The collection and measurement of some fifty giant sequoia sequences, together with general climatic studies, received the generous assistance of the Carnegie Institution. The collection of specimens and dating of prehistoric ruins in Arizona and New Mexico back as far as 919 A. D. was most helpfully financed by the National Geographic Society. The Research Corporation of New York, the American Museum of Northern Arizona and a number of friends have each made important and valued contributions. The University of Arizona has given a substantial portion of my time.

The discovery in 1911 that dates of individual growth rings may be recognized areas has resulted in the building

¹ Based on a lecture delivered at the Administration Building of Carnegie Institution of Washington.

nized accurately in tree after tree over of a 1,200-year tree ring chronology in Arizona and New Mexico, and has placed the interpretation of tree growth on a climatic basis. The development in 1913 of a method of cycle analysis of greatly increased efficiency gave a completely new approach to the type of cycle here involved, that is, the apparently discontinuous cycle. This method recognized the value of the "residual" method of plotting cycles and the rapid and flexible graphic correlations possible in the automatic cyclogram. The cycles here quoted as found in tree ring records have been picked out in the original data from a considerable range of cycle values and are not the result of tests of selected values, for a special feature of the cyclogram is the wide range of cycles visible at once. Each cycle is first recognized in its extended form, of which integrations, such as shown in this paper (Fig. 11), may be made if desired.

Any relationship between cycles in tree rings and cycles in the sun must almost certainly take place, through the medium of the weather, which influences tree growth and in turn is energized by solar radiation. Hence the relationship between tree growth and weather is of primary importance.

The theoretical basis for the climatic interpretation of tree growth may be expressed as follows: If many widely separated trees in a uniform area show the same variations in the same years con-

tinuously (that is, for hundreds of year), then these variations are climatic in nature, for climate is the common continuous factor in the life of the forest trees.

A second principle of interpretation brings us a little closer to the dominant meteorological element in the trees, namely, that a forest limit may isolate the climatic factor involved. Thus, for example, the lower pine forest border in Arizona, which separates the successful forest from the desert below, is a matter of altitude and therefore water supply, which in that region depends on altitude. The trees near this forest limit therefore give prominence to a rainfall record, though other factors are there. This is shown in Fig. 9 in which agreement is shown between tree growth and rainfall at Prescott, near the lower forest border of the Arizona pines. The lower pair include some conservation and have to each other a correlation coefficient of 72 per cent.

Fig. 10 gives us a similar comparison for Southern California areas. In the upper set, three curves are compared in their original values; in the lower set the smoothed values are shown. The first curve gives Lynch's Rainfall Indices, 1770 to 1930, for the Los Angeles area, including San Diego records after 1850. The second curve is from sixteen pines in the San Bernardino Mountains at about 6,000 feet elevation, in the large Santa Ana Valley northeast of Redlands and lying just east of the rainfall area considered. Here the resemblance to rainfall is quite evident, especially in the minima. The correlation coefficient between these two curves from 1770 to 1930 is 45 per cent. and 5 per cent. probable error, a correlation that is certainly not accidental.

The third curve ties in the sequoias, even though the correspondence is not so marked. It represents the average of four large trees that grew near General Grant National Park on steep up-

land slopes, thus avoiding the water conservation of the swampy basins. The distance between rainfall area and tree area is 200 miles. The correlation coefficient here is 28 per cent. and 5 per cent. probable error for values since 1770. This correlation was examined by Dr. Dinsmore Alter and considered very probably real. This is less than the former, as expected from the greater distance. These correlations were computed by Dr. W. S. Glock. This comparison just obtained confirms the estimate previously made that water supply, while less vital than in the Arizona pines, is still an important factor in the sequoias. The accuracy of sequoia dating was carefully checked again in 1931.

Thus the tree growth cycles shown later may be safely taken as having a strong climatic significance, with rainfall as the probable major element.

I. THE HELLMANN CYCLE

Many tree groups show, since 1850, an 11-year cycle with two crests. This cycle in actual length varies from 11.2 to 11.8 years, with perhaps the commonest value at 11.4. This compares favorably with 11.35 years, which is the average sunspot cycle length since the maximum of 1837. The two crests usually are somewhat unequal in height and in spacing and in stability. In most cases one crest comes near sunspot maximum and the other near sunspot minimum. The one at maximum is much more stable than the one at minimum.

A cycle that fits this description was found by Hellmann in 1906 in North German rainfall. It is shown in Fig. 11a. Though Hellman had little confidence in this relation to the solar cycle it seems to be sufficiently frequent in trees to justify using his name. In the figures the sunspot minimum is inverted and turned into a second maximum and carefully marked in every case. By this slight modification the eye is better able



PLATE 1: 1. NORTHERN ARIZONA PINE FOREST; PHOTOGRAPH BY U. S. FOREST SERVICE. 2. FINGER PRINT OR IDIOGRAM A. D. 890-9, A CONFIGURATION OF RINGS EXTENSIVELY USED IN CROSS-DATING. 3. THE GREAT DROUGHT, 1276 TO 1299, AS SHOWN IN CHARCOAL FROM SHOWLOW, ARIZONA; BEST ARIZONA RECORD OF DROUGHT YET FOUND; NOTE THE FAVORABLE CONDITIONS FOLLOWING THE DROUGHT.

to catch uniformity or variation in the Hellmann cycle.

The existence of this cycle and the others mentioned below is based on the cyclogram patterns in Fig. 8, in which the letters correspond to the letters in Fig. 11. The cyclogram has two important characters. It is first a plot of the differences between an exactly repeating period and the observed maxima, and so cycles become separated, since they appear as lines pointing in different directions, and second, it is not merely a plot of selected maxima, it is an automatic plot of the entire data, usually smoothed by Hann's formula. Hence it is not a plot of points here and there, it is a multiple reproduction of the data in such form that correlations become at once apparent as a new feature. Such are the horizontal alignments shown in the various patterns of Fig. 8, which correspond to a cycle length of 11.4 years. The patterns carry two examples of this alignment, one above the other, as may be seen. A two-crested sunspot cycle, such as the Hellmann cycle, produces double that number of horizontal lines. For example, the last pattern, 1, is taken directly from the sunspot cycle itself with the minima inverted. Such inversion turns it into the Hellmann form. Thus the existence of a Hellmann cycle in any pattern may be judged by its similarity to 1.

In Fig. 8a Hellmann's curve of German rainfall is extended to 1920 by the Berlin rainfall record.

In 1912-13 eighty North European trees were sampled. Several hundred dates of maximum growth between 1850 and 1907 are collected in Fig. 11b (and 8b), which gives the result of this single qualitative test in a symmetrical Hellmann cycle. The only difference from Hellmann's curve is in the greater relative height of the crest at maximum. This curve has been reproduced in extended form in Vol. I, "Climatic Cycles and Tree Growth," page 78. The cor-

relation coefficient between full curve and the sunspot numbers is $+ .57 \pm .07$.

Fig. 11c represents a group of twelve trees from Dalarne, Sweden. The mean curve of the twelve, between 1830 and 1907, based on 900 measures, places the larger maximum directly over the sunspot maximum. The minimum crest nearly disappears. The extended curve was reproduced in Vol. I, just mentioned, page 75. Its correlation coefficient with the sunspot numbers is $+ .62 \pm .06$.

In an interesting group of thirteen trees from Eberswalde, Germany, 1,100 measures, between 1825 and 1907, the minimum crest has practically gone, except in a very few cases, leaving a massive crest at sunspot maximum. This is shown in Fig. 11d. The extended curve has been reproduced in the same volume, page 75. Its correlation coefficient with the sunspot numbers is $+ .51 \pm .07$.

Six groups, 57 trees, of the nine North Europe groups collected in 1912 show in their cycle average between 1830 and 1910 a good replica of the mean sunspot cycle, as can be seen in Fig. 11e. This includes about 4,500 measures. The minimum crest occurs rarely and disappears in the average. The extended curve has been reproduced in the same volume, page 77. Its correlation coefficient with the sunspot numbers is $+ .56 \pm .05$.

Now we consider tree groups in the United States. A Vermont curve from eleven trees and some 600 measures, 1852 to 1911, shows a strong 11-year cycle with one crest much more prominent than the other, and two or three years phase displacement. The range of variation is about 28 per cent. of the mean value. The correlation coefficient is $+ .53 \pm .06$, after allowing for lag of -3 years. Seventeen Douglas firs on the Oregon coast, 900 rings measured, 1854 to 1910, reach a single crested cycle with a range of about 10 per cent. There is also a slight lag. The corre-



PLATE 2: 4. GENERAL GRANT TREE, CALIFORNIA; PHOTOGRAPH BY THE AUTHOR. 5. COMPLACENT SEQUOIA RINGS IN WELL-WATERED BASINS. D-8, REDWOOD BASIN. 6. SENSITIVE SEQUOIA RINGS ON STEEP UPLAND SLOPES. D-5 IN SAME REGION. 7. EBERSWALDE SECTION WITH SUNSPOT MAXIMA MARKED; THE LAST IS 1905; 1894 IS DISTORTED BY A PEST EFFECT (PUBLISHED IN "CLIMATIC CYCLES AND TREE GROWTH," CARNEGIE INSTITUTION, 1919, PLATE 8A). 8. CYCLOGRAMS OF ORIGINAL DATA SHOWING HELLMANN OR SUNSPOT CYCLE CONTINUING THROUGH THE DATA; A AND F ARE RAINFALL RECORDS; OTHERS ARE TREE RECORDS; L IS SUNSPOT CYCLE WITH INVERTED MINIMA FOR COMPARISON; SEE TEXT, AND NOTE AT END.

lation coefficient is $+ .45 \pm .07$, after allowing for a lag of -2 years.

The largest American groups come from California and Arizona. These are perhaps best introduced by curves from the Southern California rainfall, using "Lynch's Rainfall Indices," as shown in Fig. 11f, extending back to 1770, a very important and useful compilation verified by the San Bernardino Mountain tree record. These indices since 1850, of course, became actual rainfall records. Smoothed curves of this rainfall have an obvious resemblance to the Hellmann cycle. Cyclogram analysis, 1855-1901, showed interference by a double-crested 14-year cycle and a short variation, apparently a little more or less than two years, which causes an apparent scattering of yearly values. Without these the Hellmann cycle becomes an excellent cycle with more than 30 per cent. range. A study is now being made of this two-year cycle to see if it can be distinguished from accident.

Fig. 11g shows the Hellmann cycle in the sequoias. This comes from the tabulated means of eleven trees, about, 600 measures, published by the Carnegie Institution in 1919. The data originally covering 1810 to 1914 have been extended to 1930 by collections in the Sequoia National Park. The trees are complacent and the range is small, namely, about 8 per cent., but the maxima are clean cut and the crests are very stable as there is little interference from longer cycles. A cyclogram study of this sequoia record extended back to 1804 is shown enlarged in Fig. 8m.

Fig. 11h shows the Hellmann cycle in the southernmost sequoia grove, south of Sequoia National Park and near Springville, where three 3,000-year trees have been found. This curve is made from 500 measures covering 1805 to 1890. The topographic conditions are good but not the very best obtainable for a climatic record, since the area is rather flat and the ground sometimes

moist. After removing by mathematical methods a 19-year cycle, the Hellmann cycle is evident with a range of 15 per cent.

Fig. 11i shows the Hellman cycle in the San Bernardino pines, derived from 800 ring values, about 1850 to 1900; Fig. 8i uses the larger interval, 1825 to 1925. These trees grew at about 6,000 feet elevation in Santa Ana Valley, northeast of Redlands. Collection and measurement of this group was made with the generous help of Mr. J. J. Prendergast, president of Bear Valley Mutual Water Co. Here a 14-year cycle was strong. On subtracting it from the data the Hellmann cycle shows a range of 16 per cent., and probably more.

The Hellmann curve in the Arizona pines is given in Fig. 11j. This is derived from 3,000 measures in 58 trees, distributed across two hundred miles of country, approximately including 1850 to 1905; the cyclogram, Fig. 8j, uses the interval 1825 to 1920. A 19-year cycle lasting since 1800 completely dominates the record. This was removed by mathematical methods and also a 14-year cycle, whereupon the Hellmann cycle was well marked in the curve. It shows a lag of two or three years in relation to sunspot phase. It should be added that some of the individual groups in this large assemblage of trees, such as the one from the Grand Canyon, give the Hellmann cycle in prominent form without the interfering cycles.

Fig. 8k shows Grand Canyon tree growth from seven trees, 1825 to 1920. The effect is here shown of using the center of gravity of the maxima. It produces a Hellmann cycle of very good form. There is the same probable two or three year lag, as in the general Arizona curve. A lag of -3 or -4 years fits many of the curves very well.

Fig. 8l, as already mentioned, gives the sunspot numbers with an inversion of minimum values for comparison with the Hellmann cycles from terrestrial

sources. For method of reading the cyclograms, see note at end of paper.

This concludes the presentation of the Hellman cycle in trees. At this point two notes should be made. First, this cycle is common in trees since 1850 and, second, the interfering cycles, 14 and 19 years are widely distributed cycles. The shorter one is plainly a solar cycle, as will appear later, and the longer is probably so.

II. HISTORICAL CHANGES IN HELLMANN CYCLE

Having described a cycle in tree growth that has the same length as the sunspot cycle, but usually of different shape, it is well to see if any historic changes in this cycle can assist us in deciding on its identity. In 1909, two years before exact dating was developed, a trace of Hellmann cycle was noted in the Arizona pines. In the next three years a remarkable example of Hellmann cycle was found on the wood in rings 1430 to 1530 or later. The two-crested form was noted, lasting with some interference to near 1650. There it stopped, but was resumed again later. This is shown in Fig. 12. An 11-year cycle reappeared after 1725, but it did not resume the regular Hellmann type till after 1800. Even then it was partially hidden by interfering cycles. The complete failure of the 11-year cycle during the interval from 1660 to 1725 caused at the time much doubt of any significance in the apparent relationship to the solar cycle. All this was published in 1919, with full reference to the failure near 1700. In 1922 Maunder published an article on the great dearth of sunspots from 1645 to 1715, and gave me my first information regarding that phenomenon. During the dearth, sunspots were very rare; two intervals of 10 years and four or five of 5 years show no sunspot records at all. Under such conditions it is quite evident that estimates of sunspot minima have no

value and dates of maxima are none too good, for very large spots may come at almost any time in the cycle. This coincidence between the failure of spots and the failure of the 11-year cycle in trees was a source of great interest to Dr. Maunder and myself and greatly strengthened the solar explanation of the Hellmann cycle in trees.

On the occasion of publishing some account of this in 1928, it seemed worth while to find what cycles, if any, replaced the 11-year cycle in tree growth. The Arizona trees answered at once with a 10-year cycle. Four sequoias, which generally seemed to show more 11-year cycles than the others, gave a plain 10-year cycle during the dearth of sunspots. Many sequoias showed cycles also at 8.5 and about 14 years. A long hemlock record in Vermont gave 20 and 28 years with probable half values at 10 and 14.

So it seemed necessary to examine the sunspot record with more care, to find how it compared with these results. The maxima assigned by Wolfer were plotted and analyzed, and it was evident that a 10-year cycle between 1615 and 1788 would fit as well as the usually accepted 11-year cycle. On trying it out the average residual is just about the same. But if one uses Wolfer's weights, as of course one should, the average residual decreases 25 per cent., thus giving some preference to the 10-year cycle and producing agreement with the tree records.

All this is exceedingly difficult to show in the form of a plot or diagram, because with the exception of the cyclogram method, used since 1913 in these studies, there is no adequate way of representing the mixtures, the changes, the continuities or the interruptions of cycles in a single plot. I am therefore showing in Fig. 13 a certain form of plot specially adapted to presenting cycles. It gives on ordinary rectangular coordinates the residuals between an exact

cycle and the observed cycle. If the residuals are constant the plotted points form a horizontal line. If in any part of the diagram the residuals are changing at constant rate, they must form a straight slanting line. But any set of residuals changing at constant rate is merely expressing a cycle of different length. Thus the direction taken by any row of plotted points becomes a measure of cycle length. This is the important feature and to such a plot the name of cyclogram is given. So in Fig. 13 in plots 1 and 2 the horizontal alignment in the right half, mostly since 1800, represents the 11-year sunspot cycle. Before 1800 the line is on a slant pointing (if it were on a clock dial) toward 2 o'clock. This indicates a 10-year cycle. The 1 o'clock line is an $8\frac{1}{2}$ -year cycle. The 5 o'clock line is a 14-year cycle.

The uppermost of the four plots produces a characteristic Hellmann effect by including sunspot minima as well as maxima (See also Fig. 8L.) The 10-year cycle effect in the left half is more conspicuous than in the second line giving sunspot maxima only. The second plot shows the alternative possibilities of 10 and 11-year cycles in the maxima. Plot 3 gives the obvious 10-year effect in Arizona pines from 1600 to 1800. And the fourth shows a similar plot of the eleven sequoias, whose measures were published in 1919. Here the 10-year cycle is faint, but $8\frac{1}{2}$ and 14-year cycles are very clear. While these cycle values appeared during the dearth of sunspots, they appear at other times also and can not be considered as specially characteristic of that solar condition. The characteristic of that time is the absence of the 11-year cycle in tree records that show it before and after.

Fig. 14 presents the same facts in a less elegant but better known form. Here the tree record indicated by a solid line begins two hundred years before the sunspot record indicated by a dotted line. The Hellmann cycle shows strongly in those two centuries.

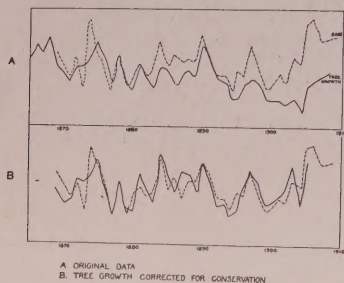
This is followed by a 10-year cycle in tree and sun during the dearth interval. In the last hundred years the agreement is resumed on the 11.4-year basis. Thus in the dominant cycles, 10 and 11 years, the trees change with the sun. The minor cycles, $8\frac{1}{2}$ and 14 years, are generally present in each. The presence of these cycles in the sun is shown independently by the cyclogram process, and by Schuster's periodogram, as will appear in the next part of this paper.

In summarizing this section upon historical changes in the Hellmann cycle two items should be noted. First, after having traced the Hellmann cycle through the 1400's and 1500's, into the 1600's when sunspots were well seen, we find that it disappeared when there was a great dearth of sunspots, and reappeared when the spots came back. During the dearth there existed in the trees three solar cycles, of which the 10-year cycle was prominent in the trees and probably in the sun. This historical agreement between trees and sun offers the second definite argument that solar changes do influence tree growth.

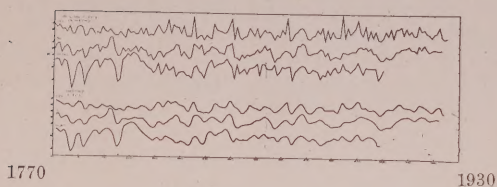
The second note is this: To change these residual plots into the best cyclogram form as used for years, it is only necessary to add one or more duplicates of the plotted points at proper spacing below. It then became possible to trace alignments of residuals over much greater range and several differing cycles can be seen at once in the form of lines pointing different ways, and beginnings and endings may be determined as well as variations, discontinuities and change of phase. In full cyclogram analysis this diagram is produced automatically and can be varied in continuous progression over a wide range of cycle lengths. It should be carefully realized that cyclogram treatment does not exclude mathematical treatment, it precedes it; that is, it tells where the mathematical study is best applied.¹

¹ The inadequacy of harmonic analysis may be illustrated in this way. Suppose we have a

9



10



11

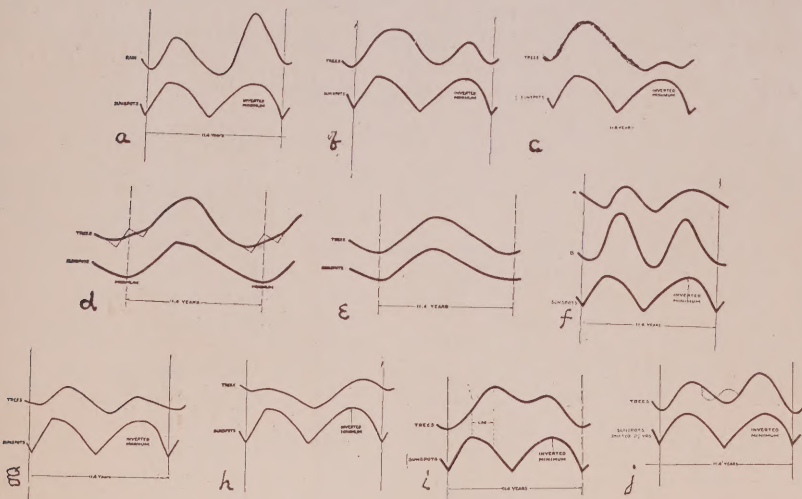


PLATE 3: 9. PRESCOTT TREE GROWTH AND RAINFALL, REGION OF LOWER FOREST LIMIT. (PUBLISHED *ibid.* PG. 68.) 10. UPPER THREE CURVES SHOW LYNCH'S RAINFALL INDICES, 1770-1930; SAN BERNARDINO MOUNTAIN PINE RECORD AND UPLAND SEQUOIA RECORD: LOWER CURVES ARE THE SAME SMOOTHED. 11. HELLMANN CYCLES OBTAINED BY INTEGRATION OF DATA USED IN FIGURE 8; SEE TEXT; CORRESPONDING SUNSPOT PHASE IS SHOWN IN LOWER CURVE.

III. CYCLES IN PAST CLIMATES

A third group of results gives added weight to the probabilities of a solar relationship brought out in the last topic. It deals with the more general question: What groups of cycles are found in tree records, and are they related in any way to solar cycles?

Forty-two groups of western pine, 305 trees with 52,000 measures, have given us by analysis a large number of cycles (published in 1928). Each analysis was checked by independent tests on inverted curves and altered time scales. It was noted as early as 1926 that the cycles were distinctly grouped about values that bore simple ratios to the 11-year sunspot cycle. This was published in 1928 (January) and the more finished results appeared in 1929 in "Conferences on Cycles," issued by the Carnegie Institution. In the month of the first publication, C. E. P. Brooks published a result of similar nature derived from the Nile Gauge Readings. Clayton, a little later, noted the unexpected great relative importance of simple fractions of the 11-year solar cycle, and Abbot has dealt with radiation varying in short-cycle lengths, similarly connected with the solar cycle.

Cycles obtained in modern tree ring records are indicated in Fig. 15, upper line. They are $8\frac{1}{2}$, 10, 11.4, 13.5, to 14.5, 17 and 19 and others still longer.

At Flagstaff, Arizona, in 1904 the writer discovered in an arroyo a tree stump in place that had been buried 16 feet below the top of the valley terrace. In 1919 and for several years after, with especial help from Major L. F. Brady, a

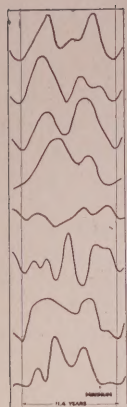
five-year cycle lasting for twenty years. If we pick out just that twenty years, harmonic analysis will show that cycle; if we try forty years, such analysis can only give the cycle at one half amplitude; if we have one hundred years of data the amplitude is only one fifth of the real value. One sees that this effect is exactly opposite to the effect on permanent astronomical cycles, which are strengthened by increasing length of data.

large number of tree sections were secured from different depths between 1 $\frac{1}{2}$ feet and 16 feet. The annual rings in the logs at shallow depth were of the sort now growing in the pines thereabouts—dry climate rings. The rings at 12 and 16 feet in depth were wet climate rings, large and showing a slow surge in size characteristic of continuous water supply. This contrast occurring in one locality appeared to indicate a climatic change. Ten of these buried trees, chiefly from the upper levels, gave excellent measured records aggregating more than 1,400 years. Here again we found cycle values near $8\frac{1}{2}$, 9.6, 14, 17 and 19, and especially the Hellmann double-crested cycle averaging 11.4 years (see Fig 15, second line).

The very remarkable clay records revealed by Professor Gerard DeGeer in Sweden and Dr. E. Antevs in North America well deserve careful analysis for cycles. Antevs' measures of the clay layers in the Connecticut Valley, left in the retreat of the New England ice sheet, received a brief preliminary analysis soon after they were published and a recent fairly complete review. His sequence, examined for cycles, covers about 4,000 years with a break in it. Careful cross-dating has no doubt given the separate parts a fine continuity. Cycles were frequently recognized between 7 and 8 years in length, shown in the third curve of Fig. 16. At 8.8 and at 10 there were strong cycles. The 11-year cycle is weak or absent. Only two good examples of it were found in the 4,000 years. A cycle appeared at 12.5 years, a group at 13 and 14.5, some at 16 and 17, and strong cycles close to 20 years. This result is essentially repeated in the 736 years of Hudson River varves recently published by Dr. Chester A. Reeds, of New York.

In 1912 a large number of fragments of swamp cypress, *Taxodium distichum*, described to me as Pleistocene, were secured in the peat beds north of Dresden.

12



1700

WESTERN PINES
MODERN

BURIED TREES
FLAGSTAFF

TERTIARY SEQUOIAS
YELLOWSTONE

SCHUSTER'S
PERIODOGRAM
OF THE
SUNSPOT NUMBERS
UDDEN'S ANHYDRITE
PERMIAN

8

STUDY OF 10 YEAR CYCLE

20

15

1600

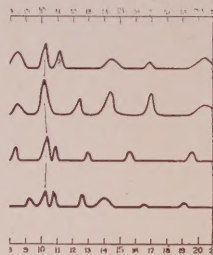
1900

TAXODIUM DISTICHUM

SUNSPOT NUMBERS
DEARTH

DEARTH CYCLES IN MODERN TREES

PLEISTOCENE VARVES, NEW ENGLAND
AND NEW YORK

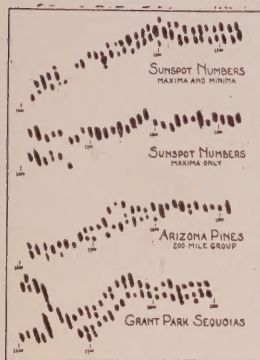


8

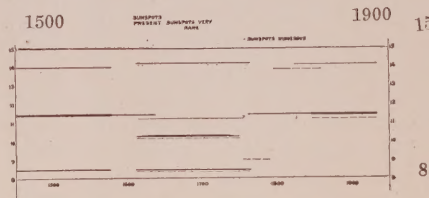
21

16

13



TREE GROWTH CYCLES AND SOLAR CYCLES
SINCE 1450



1500

1900

15

14

8

PLATE 4: 12. HELLMANN CYCLE IN ARIZONA PINES AND ITS ABSENCE NEAR 1700 IN DEARTH OF SUNSPOTS; THESE CURVES WERE PUBLISHED IN SAME VOL. I, PG. 103; THE LAST THREE SHOW INTERFERENCE OF OTHER CYCLES. 13. "RESIDUAL PLOTS," CYCLOGRAM TYPE, SHOWING DEARTH CYCLES, 1650-1750, AT $8\frac{1}{2}$, 10 AND 14 YEARS. 14. SAME PLOTTED IN TERMS OF CYCLE LENGTH AND TIME. 15. GEOLOGIC CYCLES COMPARED WITH SCHUSTER'S PERIODOGRAM OF THE SUNSPOT NUMBERS. 16. CYCLES IN ICE AGE MATERIAL COMPARED TO DEARTH CYCLES IN SUN AND TREES.

The total rings measured were 1,260 in number, distributed in four specimens giving long sequences of rings that appeared to be nearly free from errors. One five hundred year record gave a strong cycle at 10.9 years; another gave a good cycle at 10.0 years. Others were not particularly satisfactory, owing to the complacency of the growth. There are here some items of resemblance to the varve cycles just described (see Fig. 16, lowest curve).

In 1929 and 1930 collection was made of some 38 tertiary sequoias, silicified, from Specimen Ridge in the Yellowstone National Park, with results shown in the third curve of Fig. 15. These fossils were largely secured by Messrs. Mason and Reade as far as possible from one single horizon of petrified stumps. Probably many of them were living trees at the same time. Like the corresponding species, to-day, the coast redwood, they are cross-dated with difficulty, for there are no distinctive drought rings to serve as guides, as in the giant sequoias and the pines of dryer regions. The counting therefore lacks the precision of cross-dated material, but yet is thought not likely to have errors that would change the results. So each tree record was counted carefully by Mr. H. F. Davis, over 11,000 rings measured, plotted and analyzed by him. This resulted in a surprising number of cycles between 11 and 12 years. I have personally repeated the analyses and have confirmed the frequency of the prominent Hellman cycle at 11.2 to 11.8 and the usual cycles at $8\frac{1}{2}$, 10, 14, 17 and 19. Some of the sequences gave groups of cycles so closely alike that it may be possible to cross-date by that means. That is a new problem to be tested later.

Several years ago the late Professor Udden, of the University of Texas, discovered lamination in anhydrite material forming a drill core brought up from some 1,500 feet in depth in Culbertson County, Texas. He became satisfied

of the annual character of the layers and by aid of a grant from the Carnegie Institution caused them to be measured. He thought there might be an error of the order of 2 per cent. in layers lost. The longest good sequence of layers studied has 1,443 years. The measures were turned over to Dr. E. L. Dodd for cycle analysis. He made a report showing the presence of cycles at 10, 11, 19 and 33 years. I was fortunate enough to secure a copy of this series of measures and have checked the analysis and confirm Dr. Dodd's results. I find cycles at 7 to 7.5 years, 8.8, a very prominent Hellmann cycle at 11.4, a group between 14 and 15 years, a faint one at 17.5 years and a little better one at 19 years. I found only a weak cycle at 10 years, as shown in Fig. 15, last curve.

These various analyses of modern and past climates when brought together show two chief results of interest to us. First, all these terrestrial cycles from modern trees and geological sources approximate in length the cycles in sunspot numbers (see Fig. 15, fourth curve), and second, they exhibit the two types of cycle complex or mixture already observed historically in the sun and trees, namely, the present common type, dominated by an 11.4 year cycle, and the dearth type, containing a 10-year cycle with about the same minor cycles in each group. The first of these types is shown in Fig. 15. This figure brings out the agreement found in modern trees, in buried trees, living perhaps 2,000 years ago, in Miocene sequoias from Yellowstone Park, in Udden's Permian anhydrite from Texas, with Schuster's periodogram of the sunspot numbers—an evident similarity outlining an immense interval of time.

But there is evidence that this cycle complex was not continuous from Permian times to the present, for the Pleistocene varves and logs of swamp cypress, *Taxodium distichium*, probably of the same age, give the dearth cycles of sun

and trees. Fig. 16 shows the cycles in sun and trees from 1600 to 1750, and below, the varve and cypress cycles. One notes that these Pleistocene cycles resemble the terrestrial and solar cycles near 1700 A. D., when there were many successive years without sunspots.

In this review of cycles in past climates it seems difficult to avoid the conclusion that these terrestrial cycles are connected with solar cycles. At the same time we get an idea of stability in the source of these cycles, even though the terrestrial results are sometimes complex.

IV. CHARACTERISTICS IN CLIMATIC CYCLES

Attention should be called to the general resemblance between tree growth and solar cycles in their discontinuous or fragmentary character. When examined in cyclograms they look alike, save that the recent solar record is more apt to have only one cycle at a time. Before 1800, however, it had a mixture. The solar cycle is discontinuous, made up of substantial fragments. At the time of its discovery, somewhat less than one hundred years ago, it must have seemed very unstable, as a century of changes had just taken place: four cycles at about 9 years each, after 1750, then three cycles averaging 14 years, then one at 7, and then one or two at 11, but since that time it has been very constant at about 11.4 years.

Cycles in trees and climate seem apt to display similar changes, but they also display more cycles at one time, thus causing confusion. This may be persistence of cycles after the cause has changed, possibly a biological character. The cause may be persistence of cycles in the sun in some form less conspicuous than the usual smoothed annual sunspot numbers. Records in trees are very subject to a strong 2-year variation in which successive years tend to present opposite extremes. A similar character

in weather has often been discussed, and similarity may be found to the cycle of 25 months quoted by Abbot in his solar radiation work. We must remember that cycles of two or three units are the most frequent to occur in accidental data. An approximate two-year cycle could be the cause of the great scattering of individual yearly values in rainfall and tree growth. In a large part of the analyses here quoted, the tree record has first been smoothed by a very simple formula $N = \frac{(n-1) + 2n + (n+1)}{4}$, which

nearly eliminates the 2-year variation and gives an opportunity for longer cycles between 5 and 35 years to be observed.

Extensive testing work has been done to find if the long tree records can be distinguished from accidents and it is found that they can be so distinguished, if 150 or 200 years in length. The first criterion is the presence of a greater number of long cycles. This establishes a different type of periodogram from accidental sequences in which increasing prominence is given to the shorter cycles.

We find in terrestrial records certain long cycles that result from interference between short solar cycles already mentioned. In the solar records we have the Hellmann cycle and also a cycle at $8\frac{1}{2}$ years; the interference time between these two is 34 years, which gives us the Brückner cycle, frequently observed in tree growth. It is mentioned by Dr. Dodd as present in Udden's anhydrite measures from Texas. The interference between 14-year cycles and 11.4 is about 57 years. The Arizona trees show a strong cycle of this length between 1170 and 1500 A. D. The interference between the most common values of the 10 and 11-year cycles (about 10.3 and 11.4) is closely 100 years. This cycle was noted by Michelson in his analysis of the sunspot numbers. Many years ago it was found by the writer in Hunt-

ington's measures of the big sequoias as very prominent for nearly 2,000 years. Later it has been confirmed, but not specially studied, in accurately dated sequoia records. In the 1,200-year Arizona pine record a 100-year cycle is very prominent, indeed. All these scattering items sustain the idea of a relationship between the changes in the sun and the cycles in tree growth.

V. CONCLUSION AND COMMENT

The dating and measurement of the 250,000 annual rings of trees and the application to them of improved forms of cycle approach and an assured climatic interpretation of tree growth lead us to view climatic cycles as real cycles, distinguishable from accidents if shown in long sequences; appearing in a mixture of three or four cycles, long since found in sunspot records. The cycles seem to be discontinuous but occur in substantial fragments. Of these the most important is the Hellmann cycle, which in accordance with the evidence given above is considered to be a terrestrial reaction to forces operating in the body of the sun and caused through the agency of solar radiation.

In lack of a line of physical causation the relationship here stated is based on circumstantial evidence, but that evidence is very strong and a physical relationship through radiation is entirely reasonable. In fact, in these days it is not denied by any one that solar changes must effect terrestrial conditions; it is merely felt that such effects are too small to be found. The result of these tree ring investigations then shows that such effects are sometimes large enough to appear extensively in the growth of trees.

If climatic and tree growth cycles are discontinuous, can they be made of value in prediction? The answering thought is that long-range prediction, if possible, is far in the future. We must first know the actual climatic cycles as they are and

then discover, also, the factors that bear upon their interruption. A considerable number of beginnings and endings seem to be associated with the centennial disturbance above referred to. In regard to shorter cycles a considerable number have been found to begin or end at sunspot minimum or maximum, with a probable preference for the minimum. Yet sometimes a short cycle passes through a minimum without change. Important information on this subject will be found in the immensely long records of the giant sequoias. The Hellmann cycle, and other cycles that seem to be associated with it, reappear at various times in the last 3,000 years. When these various recurrences are analyzed for a major cycle, some length of the order of 280 years has seemed to apply successfully. This particular study has received the name of "cycle succession."

It must be fully recognized that thus far we have dealt with very limited parts of the world. There are, for example, stores of information in our southern forests. We know practically nothing of the tree reaction in the southern hemisphere. Fine groups have been obtained from near the northern Arctic Circle, but not yet accurately studied. It is perfectly evident that the distribution about the earth of the effects of radiation from the sun must be very complex. Yet I can not agree with the meteorologists who consider that the complexity of this distribution accounts for all climatic changes. I think, on the contrary, it is a question of hard work to find regions in the world whose climatic changes can most easily be related to solar influence, and then persistent work is needed to understand the regions that are more complex. Perhaps some regions are too complex ever to give satisfactory solution, but as a better idea is developed of the nature of solar and terrestrial changes, we will be able to gather together data bearing upon world

changes. Probably it is another problem like that of distribution of tides.

Lastly, the next obvious step is to develop the biological reaction, the relation of ring width to environment and especially to climatic elements. It is true that there are some localities where a single element, like rainfall, dominates the growth, but even here other factors have influence and in most cases the interaction is very complex.

Upon the heels of this development we must have a mathematical technique specially adapted to the study of temporary and double-crested cycles; and finally an urgent need, and one difficult to satisfy, lies in the increased development of knowledge of the physics and mechanics of the solar atmosphere.

METHOD OF READING CYCLOGRAMS

The method of reading cyclograms may be illustrated by an enlargement of Fig. 8 *g* and 8 *m*. Here, as in all cyclograms, each dot represents a full crest in the original curve whose analysis produced the diagram. The cyclograph, or analyzing instrument, is so constructed that, when set to analyze at a certain cycle length, the primary alignment of dots will be horizontal if the curve con-

tains that cycle length (Fig. 8 *m*, A-A'). Simply for advantage to the eye, the primary row of dots is repeated two or more times in each pattern (Fig. 8 *m*, A-A' and A-A'). Now if a faint row of dots (B-B') appears between the main horizontal rows it means that two crests in the curve rather than one represent the particular period at which the analyzing was done. The entire series of diagrams in Fig. 8 was photographed with the cyclograph set at 11.4 years. Hence one may readily see not only that the 11.4-year cycle is present and dominant but also that in the majority of cases it possesses two crests which, by definition, represent the Hellmann cycle.

If the curve under analysis possesses a period different in length from the one at which the instrument was set, its presence will be revealed by an oblique or secondary alignment (Fig. 8 *m*, C-C'). The row of dots, D-D', indicates the double-crested nature of the cycle represented by C-C'. In fact, the slant downward to the right in Figs. 8 *g* and 8 *m*, as well as in *h*, *i*, *j*, *k*, and *l*, is caused by a double-crested 14-year cycle which, it is evident, exists both in the tree records and in the sunspot numbers.

THE LANGUAGE OF TREE RINGS

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THE idea of studying tree rings was conceived by Dr. A. E. Douglass, of the University of Arizona, in 1901 while on a buckboard trip through the great pine forest of northern Arizona. His interest in solar changes, especially the sun-spot cycle, led him to wonder if by chance that cycle might in some way influence the amount trees grow during a year. If such should be the case, the record of sun-spots by one stroke would be pushed several centuries back of any records kept by man. It might be, of course, that the sun does not act directly on the trees but acts through an agent, such as some phase of climate. If so, climatic records would also be greatly extended. Thus he reasoned, and the trees themselves in the years that followed have testified to the correctness of the reasoning.

HOW TO READ TREE RINGS

If one carefully examines sections of trees which lived together as neighbors he will notice that the rings are not all of the same size but that in many cases they vary a great deal in width from narrow to average and up to big. A passing acquaintanceship will reveal this variation in width. Permanent friendship, however, will establish such familiarity with the individual rings of a single specimen that the identical rings can be recognized in an adjacent tree. Therein lies not only the thrill of discovery but also one of the secrets of reading tree rings.

Evergreen trees, such as pine, fir, and piñon, are more easily studied perhaps than others. With the coming of spring the tree awakens rather suddenly from

its winter sleep. Growth is rapid at first and the wood formed is light-colored and porous. As summer advances, growth gradually slackens. The light-colored wood merges into a band which is darker and denser. When winter shuts down, the tree "closes shop," so to speak, and all growth ceases so abruptly that a sharp line marks the outside boundary of the wood put down during the spring and summer. Therefore, an annual ring consists of the light-colored wood, or spring growth, plus the dark-colored wood, or summer growth, and it is marked off by a sharp line at its beginning and one at its end. We are often led to say, for the sake of brevity, that an annual ring extends from the sharp outside of last year's ring to the sharp outside of this year's ring. Since we know such to be a fact, the art of ring reading lies in the acquisition of great familiarity with the variable sizes of rings and the invention of some scheme whereby the characteristics we come to recognize may be set permanently and usefully on paper.

Let us then return our thoughts to the subject of ring variations. If we obtain a collection of a dozen or so specimens from a certain locality and at leisure familiarize ourselves with the rings we will very soon notice that each ring possesses a surprising amount of individuality, so much so in fact that a very narrow ring on one specimen can be recognized in counterpart on most of the others. It does not take long until here and there on different specimens we can pick out rings very closely alike. The feeling comes to us that we are following something which repeats itself in

the different trees, something which is telling the same story over and over. Now, if we count out from a narrow ring we will find, say, the sixth ring very narrow, and the tenth and twelfth. These telltale rings, spaced at constant intervals on all specimens, establish with certainty the close relationship among the trees and the similarity of their records.

Ring sequences quite commonly possess outstanding configurations which serve as "finger prints" of identification in every sense of the words. One series of rings we have at hand reads in part as follows: ring No. 3 small; 4 and 5 about average; 6 rather small; 7 small; 8 to 11 average; 12 small; 13 average; 14 to 16 big; 17 average; 18 rather small; 19 to 21 about average; 22 rather small; 23 and 24 about average; and 25 and 26 very small. Another series gave the identical intervals as listed save that each number was greater by 20, thus: 23 small; 24 and 25 about average; 26 rather small; 27 small, and so on. Such configurations are just as striking, just as characteristic and just as symbolic of tree identity as is the pen and ink signature of personal identity. A wood section showing a signature reveals its intimate secrets as surely as a museum specimen with a glaring label.

The comparison, *i.e.*, cross-dating, of our group of trees can be verified by paying attention to the dates on which the rings were grown. Suppose the trees were felled in the late autumn of 1920. All outside rings were formed during 1920 and represent that year. We count inward and place a single pin prick on 1910, three on 1900 for the century mark, one on 1890 and so on, and two on 1850. Narrow and big rings and the intervals between them can now be directly compared by the dates. We notice in particular the rings for 1913, 1904, 1902, 1900, 1880 and 1864, for

example; they are small in all the trees. It should be pointed out hastily that we judge a ring to be small in relation to its near neighbors only, especially the two or three immediately preceding, and not upon what we might decide beforehand should be a typical size. Since ring widths are judged relative to each other, even a group of small rings will generally possess a few rings narrower than the rest. It is this possession of very small and very large rings spaced at constant intervals and existing consistently over a homogeneous area of country which makes it possible not only to cross-date from tree to tree with certainty but also to plot a curve of the ring widths in order to show the varying success of the tree in its environment.

So far the reading of tree rings appears to be quite a prosaic task but when apparently we are forced to crowd eleven rings into, or stretch nine rings out over, a ten-year interval, then tree rings become fascinating and challenge us to read the story they have to tell. Eleven annual rings in ten years is so obviously impossible that somewhere there must be a false ring which at first sight has the appearance of an annual. It is well at this point to recall two facts: (1) the annual ring extends from the sharp outside of last year's ring to the sharp outside of this year's ring, and (2) the annual ring itself consists of light-colored spring growth plus dark-colored summer growth, the light merging forward gradually into the dark, and not the reverse. Now, if we examine the ten-year interval closely we shall probably find somewhere a band of dark wood which fades into the light wood on both sides, indicating that the tree began to form typical late growth material rather too early in the season and had to return to early growth for a time before the actual growing season ended. We call such a ring a double

because of the two dark bands, one of which fades on both sides and the other of which fades on the inside and ends in a sharp line on the outside (Fig. 1). The double, or "false ring," usually lies just inside the band of true late growth.

Occasionally a thin line of summer wood lies in the middle of what otherwise would be a single annual ring. Is it a so-called "mid-line" or is it the outside of a separate annual? The entire circumference of the tree may have to be examined in order to reach a decision. If the line moves over so as to unite with an adjoining dark band, then it is not a mid-line, but part of a separate annual ring. If the line does not move over, but ends "in the air," it is a true mid-line. Another method remains, should the above one fail to yield a decision. All the specimens of the collection covering the same time interval must be examined. If some of the specimens lack the line under question at the appropriate place, then it is very probably a mid-line.

The presence of nine rings to cover a ten-year interval does not seem so obviously impossible since one may have been lost. Of course, it was never lost—the tree simply did not grow a ring for a certain year on that part of the trunk because of adverse living conditions. The name "missing" has been applied to such rings, and it is a good one. It may be imagined what difficulties arose

because of missing rings during the inception of tree-ring study. Before he had discovered that rings could be missing, Dr. Douglass made the following note (February 15, 1904): "I find small rings not to be depended upon. . . ." Either the intervals between two small rings did not remain constant on different specimens, or sometimes a ring was small and another time it was not. In both cases missing rings were to blame. The small ring on one specimen was absent on the other—simple when discovered but no end of trouble previously.

Diagrams (Fig. 2) perhaps will help us quickly to an understanding of missing rings. Diagram a shows ring No. 3 of average size. In b it is very small, and sometimes so much so that it is microscopic. In c and d ring No. 3 is locally absent (lo. ab., for short) over a part of the circumference, and in e it is entirely absent, or missing. We can see at once that the existence of ring No. 3 in c and d can be established by close inspection of the entire circumference. Constant carefulness will prevent our overlooking rings locally absent. The case of diagram e is different. Here cross-dating with other specimens covering the same time interval not only reveals the lack of one ring for the interval but indicates exactly where the missing ring should be supplied as well. The thorough check provided by cross-dating in the revelation of doubles, mid-lines

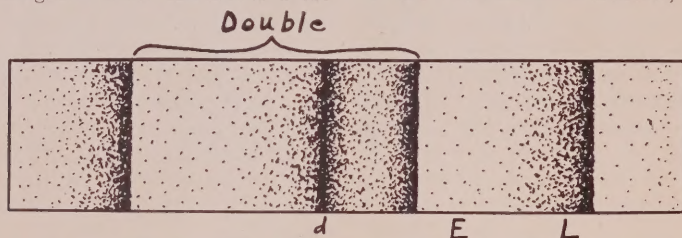


FIG. 1. THE DOUBLE OR "FALSE" RING.

THE BAND OF DARK-COLORED WOOD LABELLED "D" WAS FORMED DURING THE GROWING SEASON AND NOT AT ITS END. E=EARLY GROWTH OR SPRING WOOD FOR THAT PARTICULAR RING AND L=LATE GROWTH OR SUMMER WOOD.

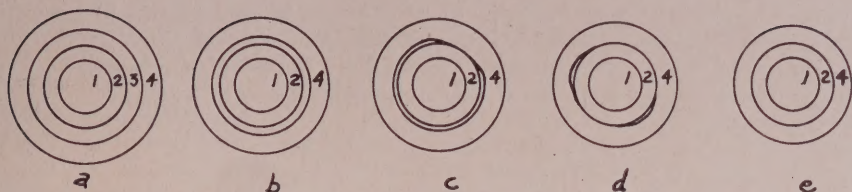


FIG. 2. LOCALLY ABSENT AND MISSING RINGS.

RING No. 3 IS OF AVERAGE SIZE AT THE LEFT AND IS MISSING AT THE RIGHT.

and locally absent and missing rings makes the process one of fundamental importance to the field of tree-ring research.

It may be of interest to quote a passage from the notes of Dr. Douglass giving the first hints of cross-dating in the dawning realization that rings on opposite sides of a tree were identical. "Tried opposite sides and find that rings on opposite sides readily identify. Identified the 1801 ring and others about 1750 and 1850 without knowing their precise place and then counted and found them correctly placed with reference to each other." The note was written on February 15, 1904. But not until 1911 was the full importance of cross-dating realized. It was the most significant step in all tree-ring studies;

it gave the needed accuracy to ring identification and a solid foundation from which to read the story of tree rings.

A knowledge of how to "read" tree rings and how to cross-date specimens will permit us to understand the construction of a tree-ring calendar, or a so-called master chart for a given region if we can devise some graphic method to represent the individual rings. To make such a calendar possible the region must possess living trees as well as material from forests which lived before the present one. A wide choice of specimens properly selected so that they dovetail together is a necessary requirement for a well-balanced, thoroughly verified calendar. Fig. 3 shows how the chain of specimens wrought out of strong links safely articulated reaches unbroken

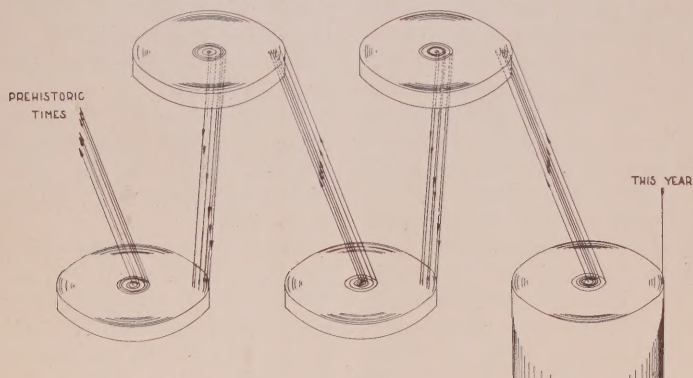


FIG. 3. THE CONSTRUCTION OF THE TREE-RING CALENDAR.

THE YOUNGEST SPECIMEN AT THE INSIDE MATCHES THE OUTSIDE OF THE NEXT OLDER, THE INSIDE OF THIS ONE MATCHES THE OUTSIDE OF THE SECOND OLDER, AND SO ON INTO PREHISTORIC TIMES.

EACH SPECIMEN BRIDGES THE GAP FROM THE PREVIOUS RECORD TO THE ONE FOLLOWING.

from the youngest ring at the right to the oldest at the left. The diagram is schematic and ideal. Nevertheless, it illustrates two things: first, that the inside of the youngest tree matches the outside of the next older and, second, that each specimen not only matches the previous one but also extends it backward in time. Thus a tree-ring calendar is built up with every ring definitely dated at a particular year if each part of the entire sequence has been verified and duplicated as much as abundance of material permits or until uncertainty no longer exists. The process whereby a ring record is extended either forward or backward in time is known as chronology building. It is accomplished by means of identifying like rings and like intervals on different specimens, as was previously explained, or in other words, by means of cross-dating.

A tree-ring calendar gives us a standard sequence of rings and represents our greatest desire for any region. In fact, the working out of a standard sequence is the initial and all-important task in tree-ring study. That done, other problems dependent upon the standard can be approached with definite hope of solution. Let us suppose, for instance, that we come into possession of a mass of material wholly unfamiliar to us. The first specimen selected shows certain noteworthy rings and certain intervals which can be recognized on a second, a third and many others. Since it is not practical to remember all the separate sequences we are justified in placing the specimens side by side, selecting those characteristic rings common to the entire lot, and holding them in mind as a standard sequence representative of the collection. True calendar dates not being known as yet, an arbitrary zero may be assigned to some one ring and the others numbered accordingly. Such a sequence is then known as a relatively dated standard, or briefly, an R.D.S.

Now an R.D.S. may occupy one of three positions in relation to the real standard sequence; that is, it may precede, follow or match part of the standard. If it matches, actual dates may at once be assigned and the problem is solved. If the R.D.S. does not match, patience must be exercised until the record has been extended far enough by means of the process of chronology building so that in the extended form it joins firmly and surely onto the dated standard. Gaps between an undated sequence and the tree-ring calendar have been bridged from time to time in the past. The most famous of the gaps, just prior to 1300 A. D., was closed by material collected by the National Geographic Society Expedition of 1929.

A little consideration will reveal the potent nature of the scheme involved in setting up an R.D.S., for it helps directly in the solution of all major problems concerned with chronology building and helps in the dating of masses of new material. In actual practise in our tree-ring laboratory the R.D.S. system is of invaluable assistance and is used constantly. Several such relatively dated standards are in existence at the present time. Should a new region fail to yield a dated standard at first, recourse must be had in an R.D.S. Relative dating has had great value in the study of collections from the ancient ruins of Indian pueblos in the Southwest and could be used in similar fashion with ancient material from other parts of the earth.

Down to here we have assumed that all ring features are held in the memory. Truth to say, the memory method of ring reading has enormous value because of its great facility and ease of application under all conditions and because the wood upon which memory is based possesses all the features characteristic of a given sequence, something no secondary method of ring representation could

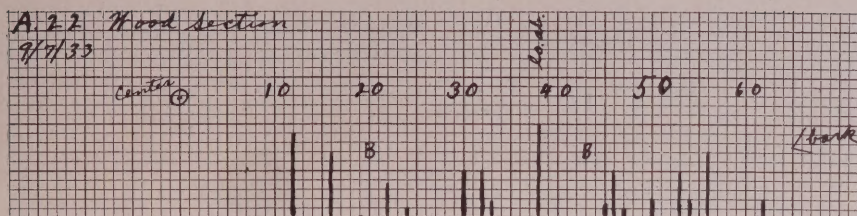


FIG. 4. THE SKELETON PLOT.

THE YEARS, AND THEREFORE THE ANNUAL RINGS, ARE NUMBERED FROM LEFT TO RIGHT ON THE PRINTED LINES. EACH LINE REPRESENTING A NARROW RING IS INKED TO A LENGTH WHICH IS INDICATIVE OF THE NARROWNESS IN THE SENSE THAT THE NARROWER RINGS ARE MARKED BY LONGER LINES. "B" STANDS FOR "BIG," AND "LO. AB." FOR LOCALLY ABSENT.

show. The memory method, however, becomes impractical if not impossible, as sequences accumulate in number. Hence it becomes necessary to devise a means of placing the diagnostic features which reveal the essential characteristics of a specimen upon paper for permanent use.

Let us take an undated specimen as an example. We count out from the center, placing a pin prick in the tenth ring, the twentieth, thirtieth, and so on. In that way each ring has a specific number. A sheet of paper is prepared by placing the number of the specimen, the date and the type of wood at the top. Then we "read" the rings. The numbers of all rings having diagnostic features are placed in a column so that telltale rings and the intervals between them are recorded. Suppose ring No. 12 is extremely small: we underline the written figure 12 three or four times. Suppose ring No. 16 is very small: we give it two or three lines. Ring No. 22 is rather small: we give it one line. Ring No. 24 is just noticeably small: it received no line. If ring No. 20 is unusually big we note the fact on the paper so: (20 B). It must not be forgotten that, throughout the whole process of reading, rings are judged small or big in comparison with their immediate neighbors only. The

sheet of paper when completed contains the so-called number plot and gives a record which is permanent for our files but which is very cumbersome to use as a record by itself.

In order to make the number plot useful in a practical and rapid way it is changed into a skeleton plot. Coordinate paper, with centimeters marked by heavy lines and with the small divisions two millimeters square, is cut lengthwise into strips four and a half centimeters wide. If one strip is not long enough two or more may be glued together, care being taken that the divisions match accurately. Each vertical two-millimeter line represents an annual ring and the lines are numbered from left to right. Ring No. 12 was taken to be extremely small; a long ink line is therefore drawn at the appropriate place on the coordinate paper. Ring No. 16 receives a somewhat shorter line than No. 12, No. 22 still shorter and No. 24 just a touch (Fig. 4). The completed skeleton plot gives us something very convenient to use, since it is easily carried about and since it can be readily placed on top of another one to see if the inked lines match, that is, cross-date.

A further word may well be given on the individual skeleton plot. If too many lines are drawn the plot becomes

meaningless. Only those rings which are conspicuous, telltale and diagnostic should be represented for the same reason that in our daily lives we are more apt to remember and compare people and places because of certain outstanding characteristics rather than because of trifling details.

Let us carry our knowledge of skeleton plots back to the collection of specimens considered previously and construct plots for all individuals. It is commonly more convenient to cross-date skeleton plots than it is to compare pieces of wood. Then, too, plots may be carried about and matched at odd moments. If plots which cross-date are placed side by side in correct position year for year the lines common to the group may be copied down on a separate strip of coordinate paper (Fig. 5). Such a procedure merges the features common to all the individuals into a single plot, the so-called standard or

master chart. Chronologies either relative or absolute are built up in this way and in actual practise the tree-ring calendar in the form of a master chart is used for dating and correlation purposes. The master chart for the Central Pueblo Area of Arizona and New Mexico built up by Dr. Douglass by the method of chronology building illustrated in Fig. 3 now reaches back more than a thousand years. It was made from living trees and from beams incorporated in the pueblos by the Indians of early historic and prehistoric times. For each of a thousand years we have a separate ring, a telltale witness to all the vicissitudes of environment, however good or bad, for tree-growth. The rings picture the life histories of the trees, the struggle against famine and the luxuriance of plenty. Each factor influencing the well-being of the tree, whether it be the soil of the earth or the rays of the sun, the snows of winter or the drought of

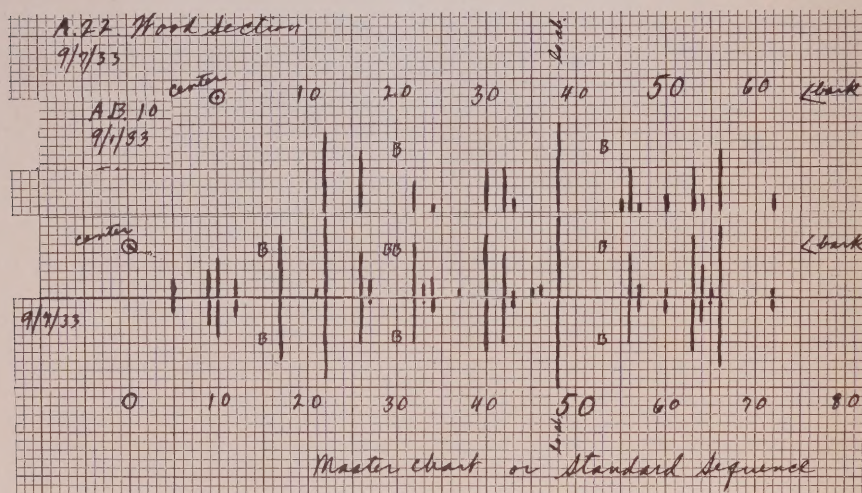


FIG. 5. THE CROSS-DATING OF SKELETON PLOTS AND THE CONSTRUCTION OF A MASTER CHART.

THE NUMBERS ON THE MASTER CHART ARE FOR ILLUSTRATIVE PURPOSES ONLY. THE PLOT LABELED MASTER CHART IS ACTUALLY A RELATIVELY DATED STANDARD IN THIS CASE.

summer, leaves its impress somewhere in the body of the tree. If we have the eyes to read we may glean bits of the fascinating story not only for the year just gone but also for a thousand years ago, and even a million years or more back in the history of plant life.

WHAT TREE RINGS TELL

Reading of tree rings and the building of chronologies are intriguing puzzles, ever leading the reader onward from one solution to another without end. The work may be difficult, painstaking and laborious as a rule; yet it comes to be viewed in the light of a genuine pleasure, time-consuming and compelling. Nevertheless, ring reading is but half the story. The application of the knowledge gained and the story written in the rings are after all the things we want to do and know. We must learn to read and understand.

The master chart, it will be remembered, shows the nature of the rings for all the years throughout its course. Suppose some one sends us from the region of the master chart a specimen which he wants dated. We examine it, and perhaps the narrow rings and intervals between them will reveal the dates. If memory fails, we construct a skeleton plot that is moved slowly along the master chart until a fit is obtained. Thus, the specimen is dated and the outside ring gives the exact date when the tree was killed or cut down. The possibilities of dating become strikingly apparent on our learning that among the Indian ruins of the Southwest we can tell to the year in most cases when the timbers were cut for the original structure, for repairs or for reconstruction by later generations.

The Indian pueblos of the Southwest are simply one example. Consider the possibilities of the system in connection with the dating of prehistoric materials

from other parts of the earth. What a revelation we may aspire to in the future! Many problems, legal, historic or scientific, may be capable of solution.

Now we must turn to the story that tree rings themselves have to tell. Fire, lightning, pest effects, wind, disease, frost—all these and others, highly interesting in themselves, leave their marks upon the growing tree, but the chief objective in tree-ring work lies along somewhat different lines. When we make a collection we desire normal, healthy trees, trees representative of the normal conditions of the environment under which they lived. A tree is more than an organism modified by its environment, it is a manifestation of that environment—a complex of cells born of and nourished in the natural products of a locality and shaped through life by the interaction of materials and forces amalgamated in the body of the tree. Each factor having an influence on the tree leaves its impress. It is a task for our eyes to learn to read the telltale signs and unravel the skein of evidence.

The personal life of a tree, whether in success or failure, in ease or adversity, is an illuminating subject for study, whether we know the exact name of the tree or not. The individual tree can not, of course, move about; it must take things as they come. When conditions are good and all factors work in harmony our trees are happy, prosperous and well fed; but when conditions are bad and certain factors become weak or antagonistic the trees are miserable, pauperized and undernourished. Tree-growth, in other words, more or less faithfully records living conditions in particular for a single locality or in general for an entire region. Since the general story should properly come first, we merge the records of a group of trees so that we may obtain an insight into

the conditions or factors affecting the forest as a whole. The following remarks are made from this larger regional view-point and, it is hoped, they will illustrate how bits of the story of the past are revealed by tree rings. For the past lives again in him who learns to read.

The mutual interaction of factors in near optimum amounts is necessary to the constant well-being of a tree. Any essential variation will leave a mark. In certain regions the fluctuations of some one factor are so important that it serves as the major control of tree-growth. Perhaps it is water supply, sunshine, temperature, behavior of the sun or others.

Let us consider the case in which water supply represented by rainfall is just enough on the average for the requirements of the trees. The average ring, then, will reflect the average rainfall. By the same token, the narrower the ring is the less the rainfall of the corresponding season, in general. A very narrow ring tells us that a tree is fighting for its existence. Times are hard, water and food are scarce, life is precarious, and a few weaker trees may die. A ring locally absent perhaps signifies that only a few of the roots were able to secure water and food: they were not sufficiently plentiful for the tree to form a complete ring. On the other hand, a large ring indicates more than average rainfall. We may well imagine the happiness and peace of mind of the tree, were it conscious, when it feels assured of plenty to eat and drink.

The double ring is of equal interest. Conditions become unfavorable in the late spring and the tree begins to "close shop," as it were, by forming some dark-colored summer wood. As the harsh conditions relax and the summer rains begin, the growth gradually returns to

the spring type for a time prior to the real end of the growing season. Thus, doubles appear to tell us of a double season, that is, a year in which the late spring and early summer drought is so severe and so protracted that the precipitation of the previous winter can not last over the dry spell.

Once interested in life in relation to its surroundings we may begin to vision the breadth of the investigation. It is not a single highway but an intricate pattern of diverging roads, each one beckoning for exploration and promising the fruits thereof.

If we measure the rings of a sequence accurately in millimeters and construct a graph of the measures plotted year by year we obtain a wavy line, or "curve," composed of successive crests and troughs. The ring measures in such form are ready for an analysis, which consists of a study of the intervals between successive crests. Since the crests represent times when the trees grew rapidly and flourished, they speak to us of causes and associations which work intermittently to the benefit of the trees. Evidence has accumulated, for instance, showing that variations in tree-growth correspond to a certain extent to variations in the sun. The sun probably exerts much of its influence through the agency of rainfall on the earth. We see at once that astronomy and meteorology lend material assistance in the study of tree rings. But observations of the sun go back only to the early decades of the seventeenth century. Therefore the rings of the giant Sequoias extending backward several thousands of years have in their turn something of value to tell astronomers. Meteorology likewise receives a long record of weather conditions. Since a forest as a whole is subject to climatic variations, the science of climatology gives as well as receives information of importance.

Archeology happily furnishes us with a wealth of prehistoric material, which on being dated supplies archeologists with exact dates of pueblo occupation. Fossil trees are not at all uncommon down in the rocks of geologic time. With our knowledge of what tree rings tell we can not only trace a lightning scar that blasted its way down a tree trunk millions of years ago, but we can also read something of the weather and climate in the dim ages gone. Are those same rings trying to tell us something of the history of the sun? Botany is not the least of the fields of man's endeavor to have a vital influence on the study of tree rings. The two studies constantly must work hand in hand. Last of all, there is the science of ecology which is intensely interested in that most fascinating of all stories on the face of the earth, the relation of living things to their surroundings. Through the whole

gamut of the sciences each has a necessary part, to give and to receive, in the ecological study of trees and the rings they create from year to year.

So we have a sort of mutual benefit association. A list of the members is rather impressive: astronomy, meteorology, climatology, archeology, geology, botany and ecology. It may not be long until chemistry and physics are invited to do their rightful share. When we consider leisurely that tree-growth not only reaches backward in time but also stretches through space to all parts of the earth we begin to see a vista of vast possibilities for the inquisitive human mind. Whole regions of knowledge await investigation. Fortunately a well-marked trail has been blazed into the unknown by the founder of tree-ring studies in whose mind the idea was originally conceived and painstakingly elaborated.

Author

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